US011245144B2

(12) **United States Patent**
Smedley et al.

(10) **Patent No.: US 11,245,144 B2**
(45) **Date of Patent: Feb. 8, 2022**

(54) **METAL-AIR FUEL CELL**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **17/036,642**

(22) Filed: **Sep. 29, 2020**

(65) **Prior Publication Data**

US 2021/0083346 A1 Mar. 18, 2021

Related U.S. Application Data

(60) Division of application No. 15/923,256, filed on Mar. 16, 2018, now Pat. No. 10,826,142, which is a

(Continued)

(51) **Int. Cl.**

H01M 12/06	(2006.01)
H01M 4/06	(2006.01)
H01M 8/22	(2006.01)
H01M 4/42	(2006.01)

(Continued)

(52) **U.S. Cl.**

CPC ***H01M 12/06*** (2013.01); ***H01M 4/06*** (2013.01); ***H01M 4/42*** (2013.01); ***H01M 4/78*** (2013.01);

(Continued)

(58) **Field of Classification Search**

CPC H01M 12/06; H01M 4/06; H01M 4/42; H01M 4/78; H01M 8/225; H01M 2004/027; H01M 2300/0014

See application file for complete search history.

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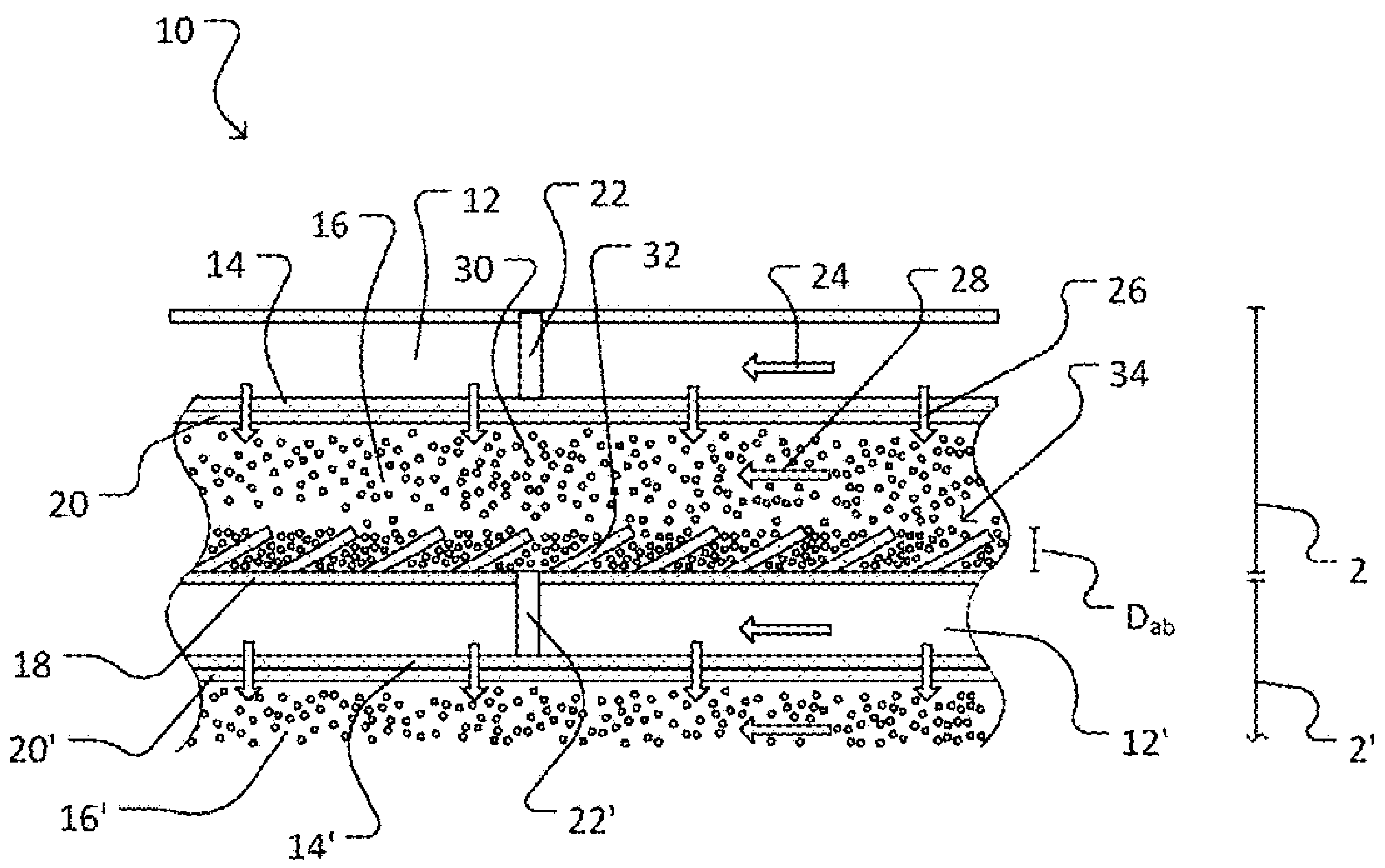
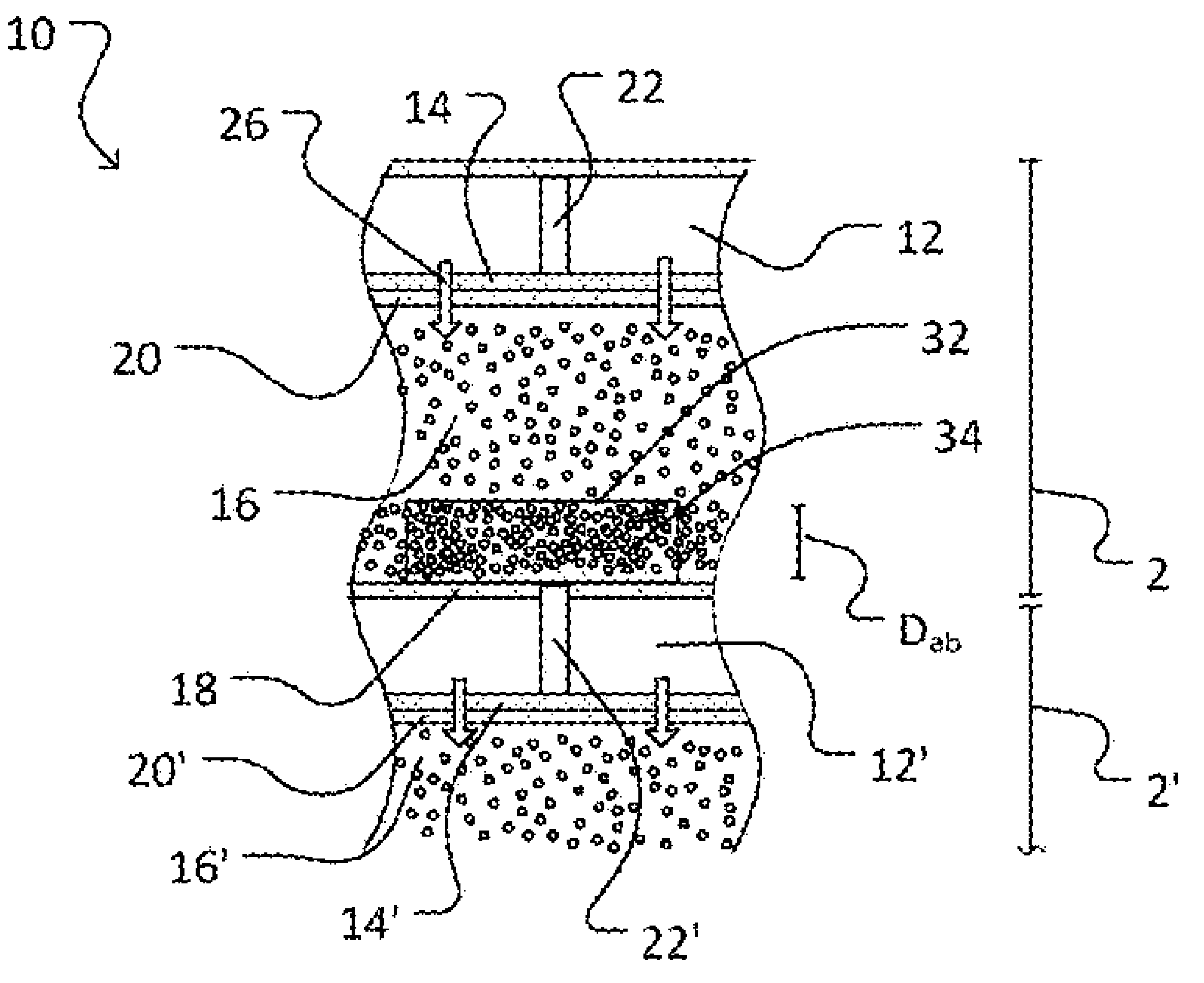
(57) **ABSTRACT**

A method of charging a metal-air fuel cell. The method includes a step of orienting an anode chamber horizontally. The method further method includes a step of providing metal particles suspended in an electrolyte to flow through the anode chamber in a downstream direction oriented horizontally. The method further method includes a step of allowing a bed of the metal particles to form on the anode current collector. The plurality of particle collectors perturb the flow of electrolyte through the anode chamber and encourage settling of the particles one of on and between the particle collectors. The method further method includes a step of maintaining uniform formation of the bed.

13 Claims, 6 Drawing Sheets





Related U.S. Application Data

continuation of application No. PCT/CA2016/051080, filed on Sep. 13, 2016.

(60) Provisional application No. 62/219,984, filed on Sep. 17, 2015.

(51) **Int. Cl.**

H01M 4/78	(2006.01)
H01M 4/02	(2006.01)

(52) **U.S. Cl.**

CPC ***H01M 8/225*** (2013.01); *H01M 2004/027* (2013.01); *H01M 2300/0014* (2013.01)

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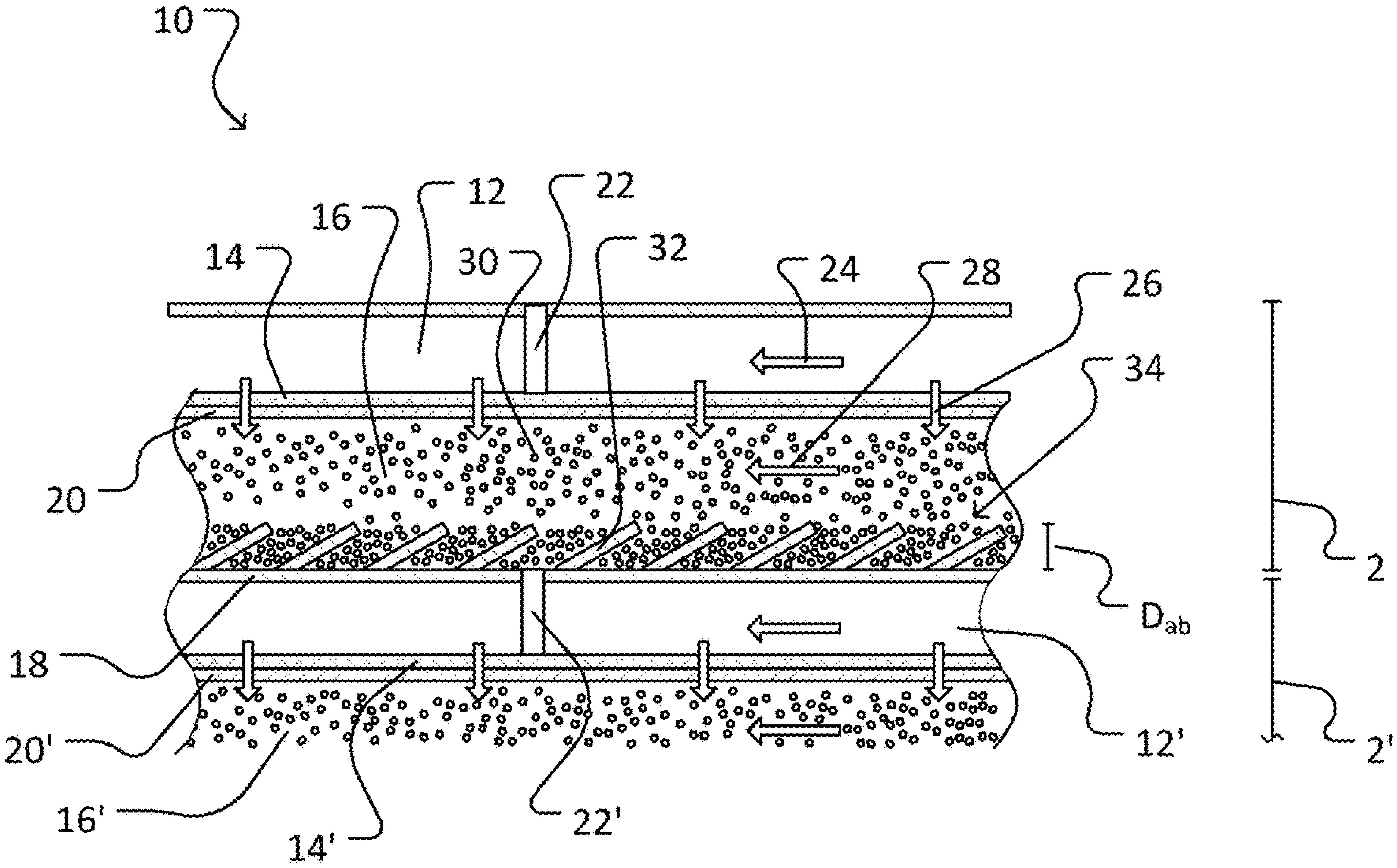
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Fig. 1A

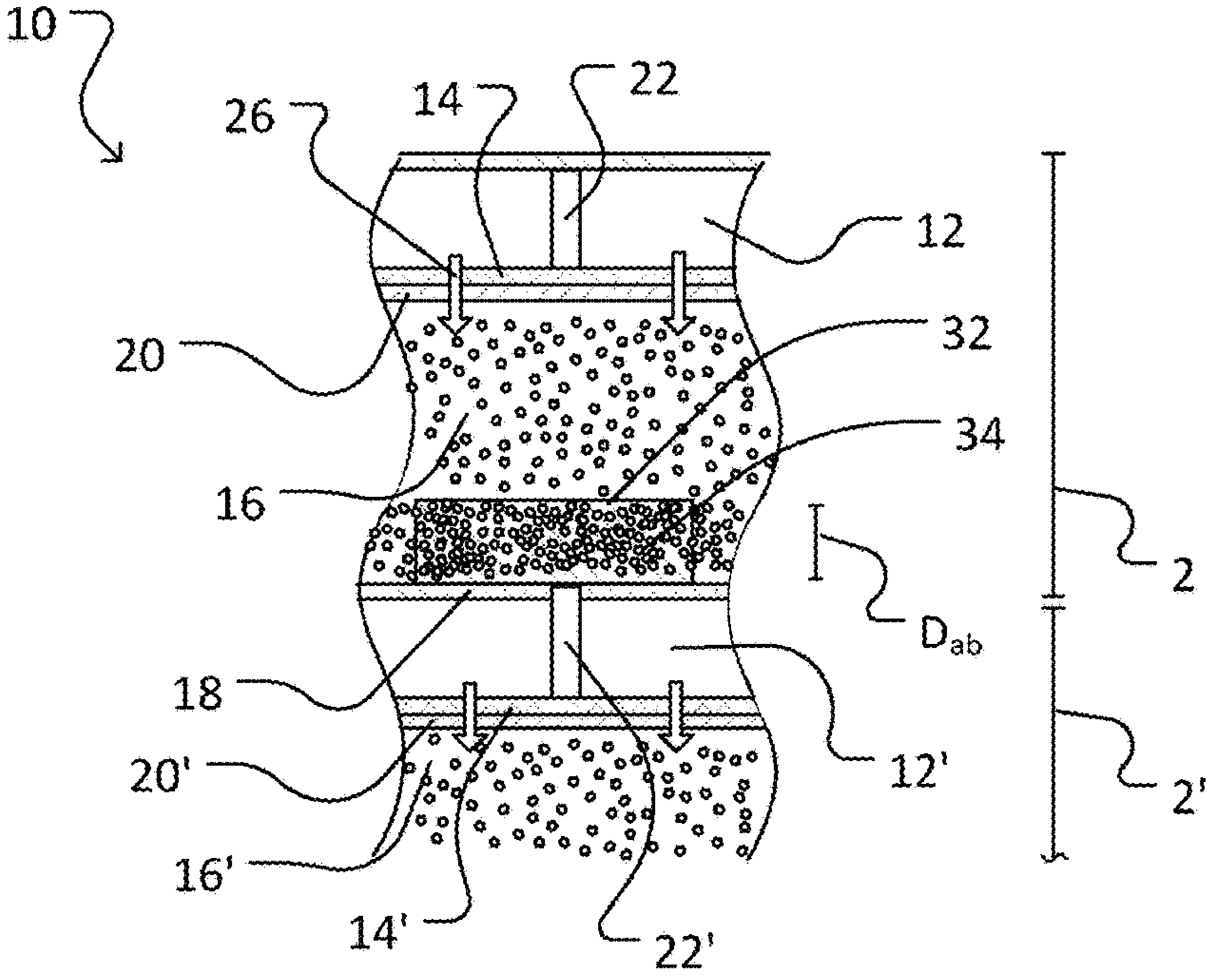
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Fig. 1B

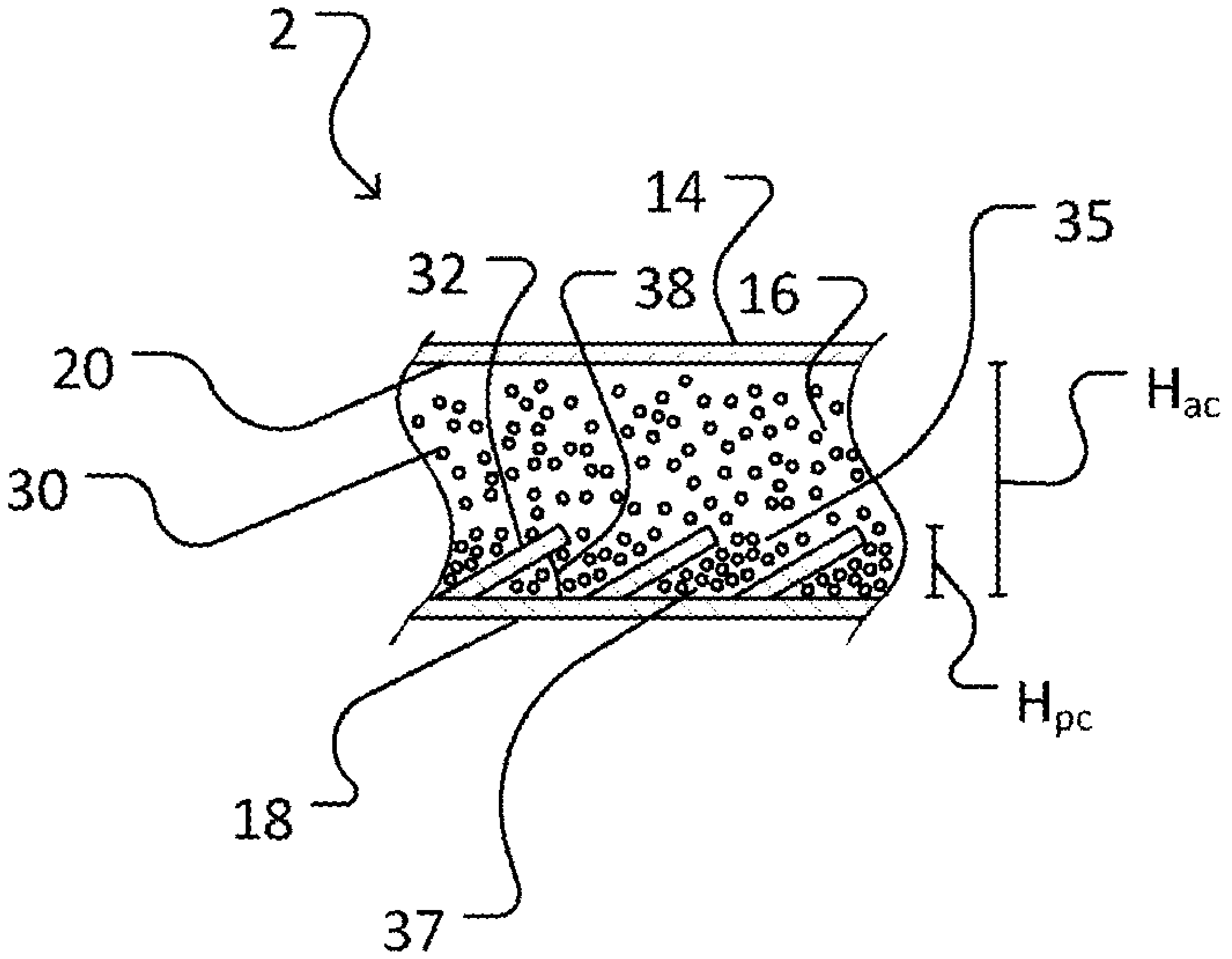

Fig. 2

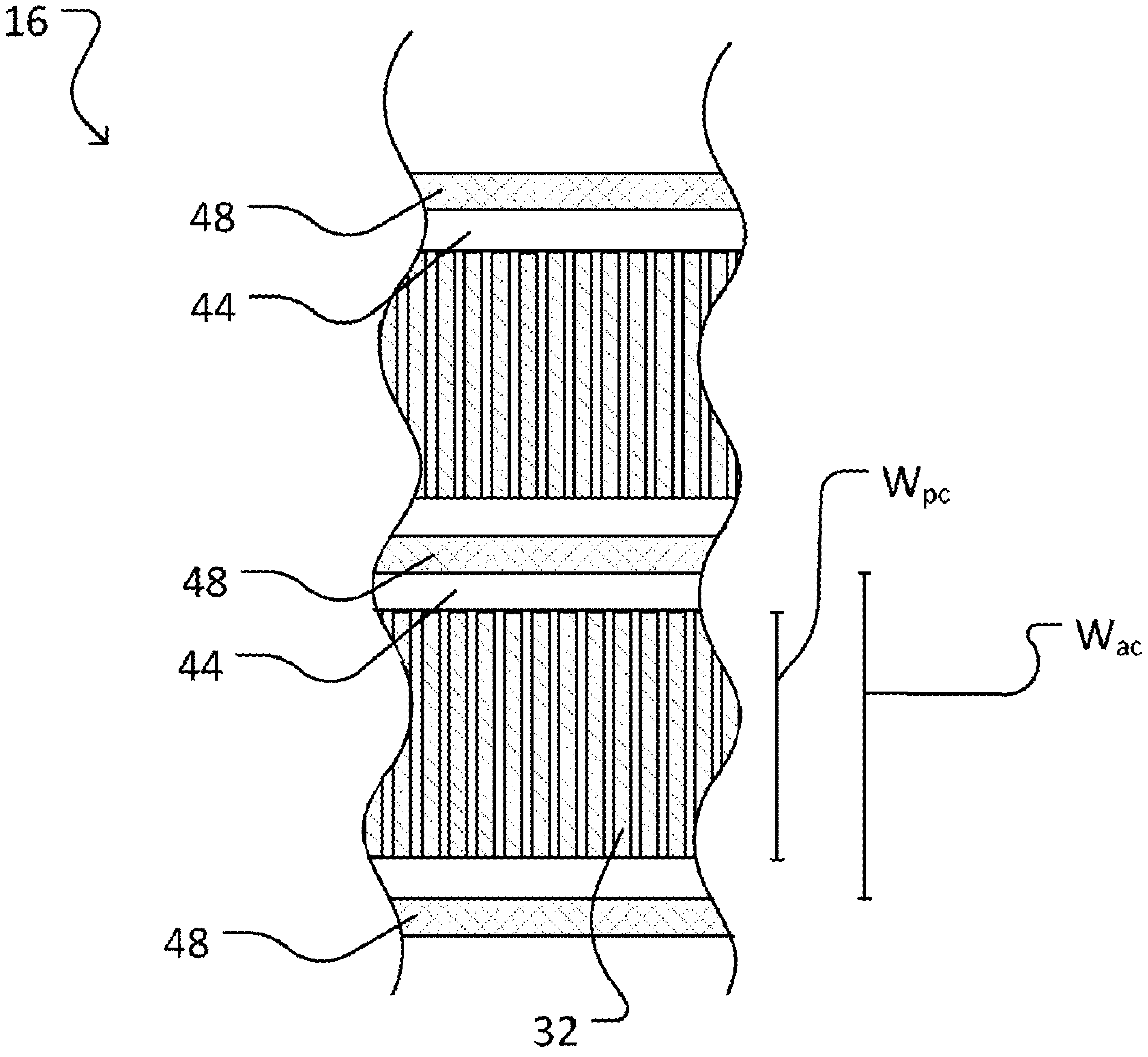

Fig. 3

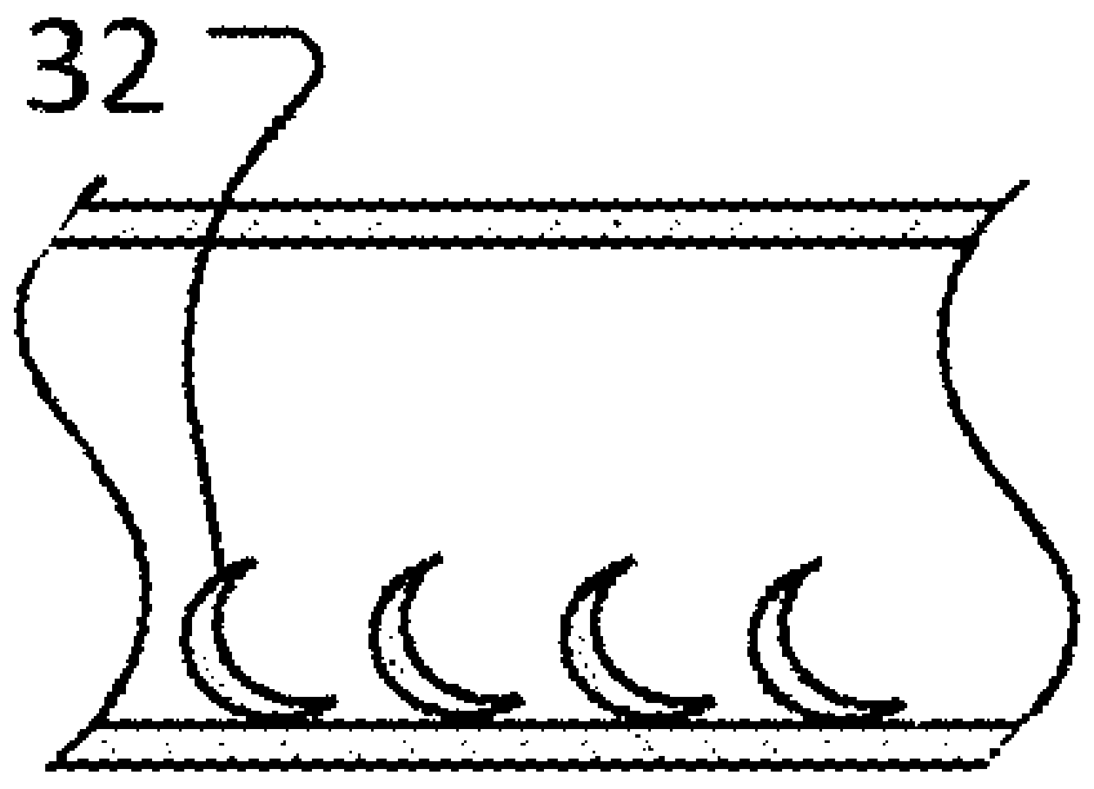

Fig. 4A

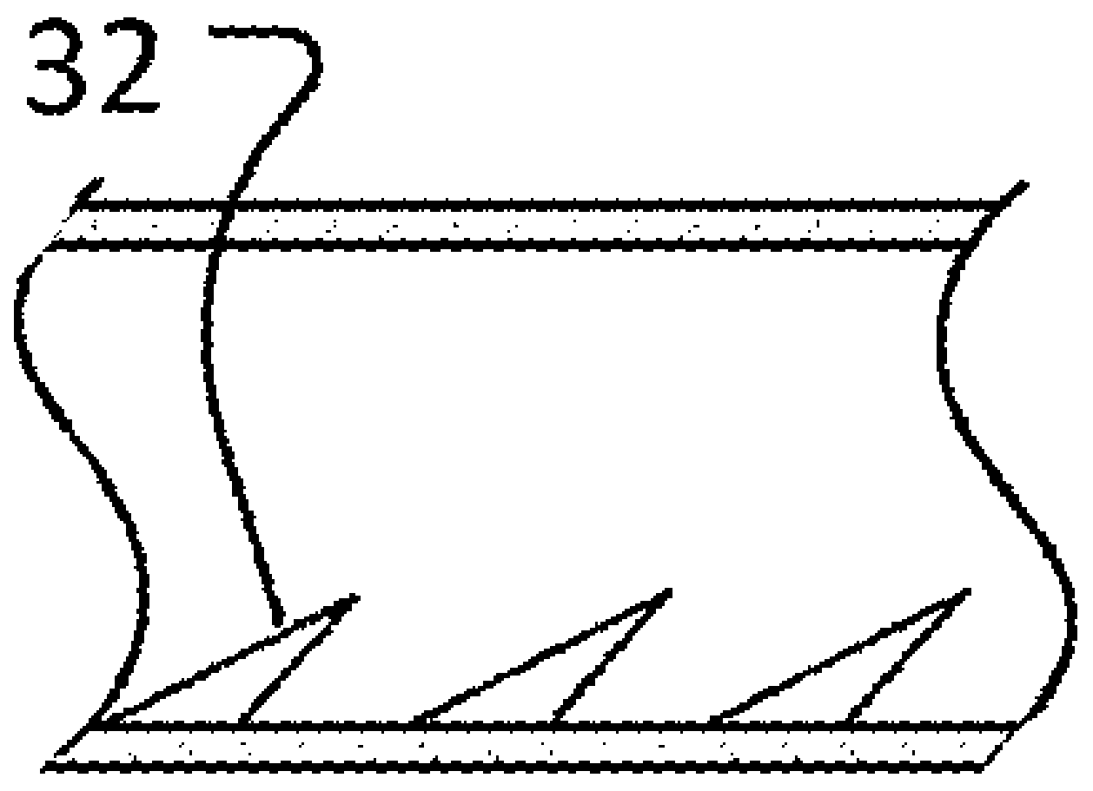

Fig. 4B

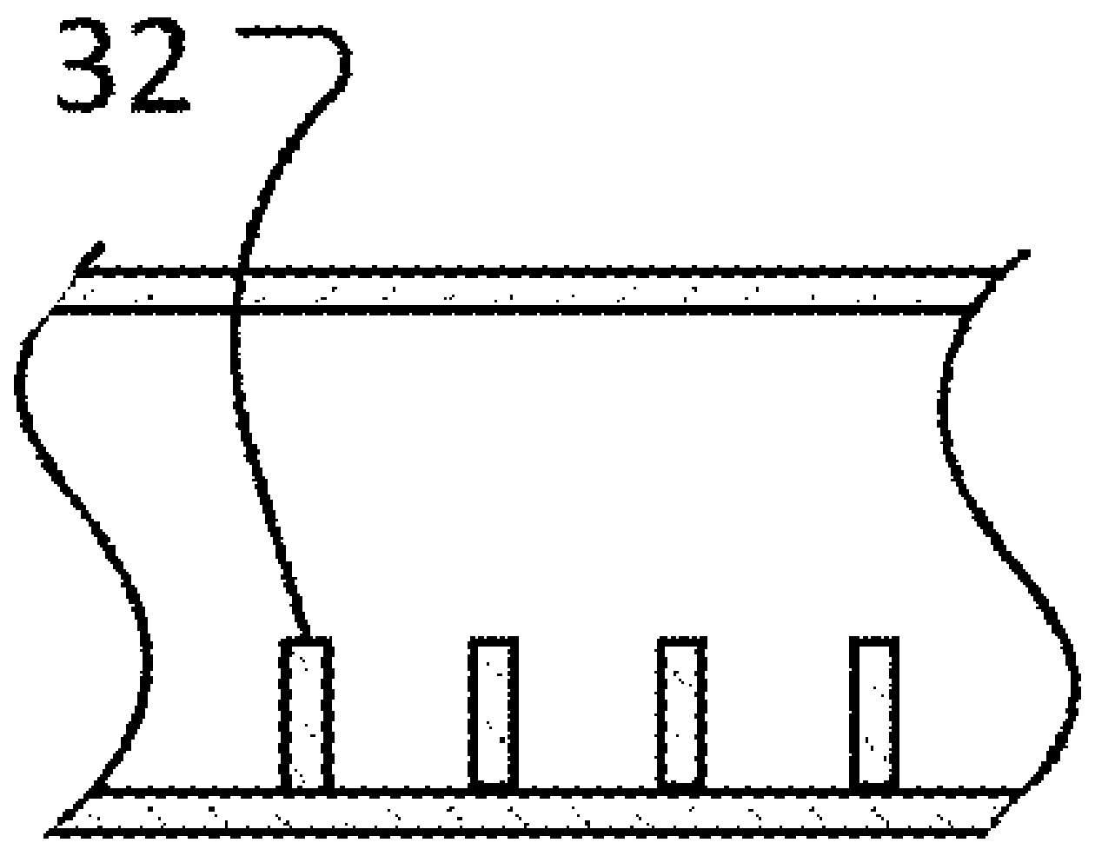

Fig. 4C

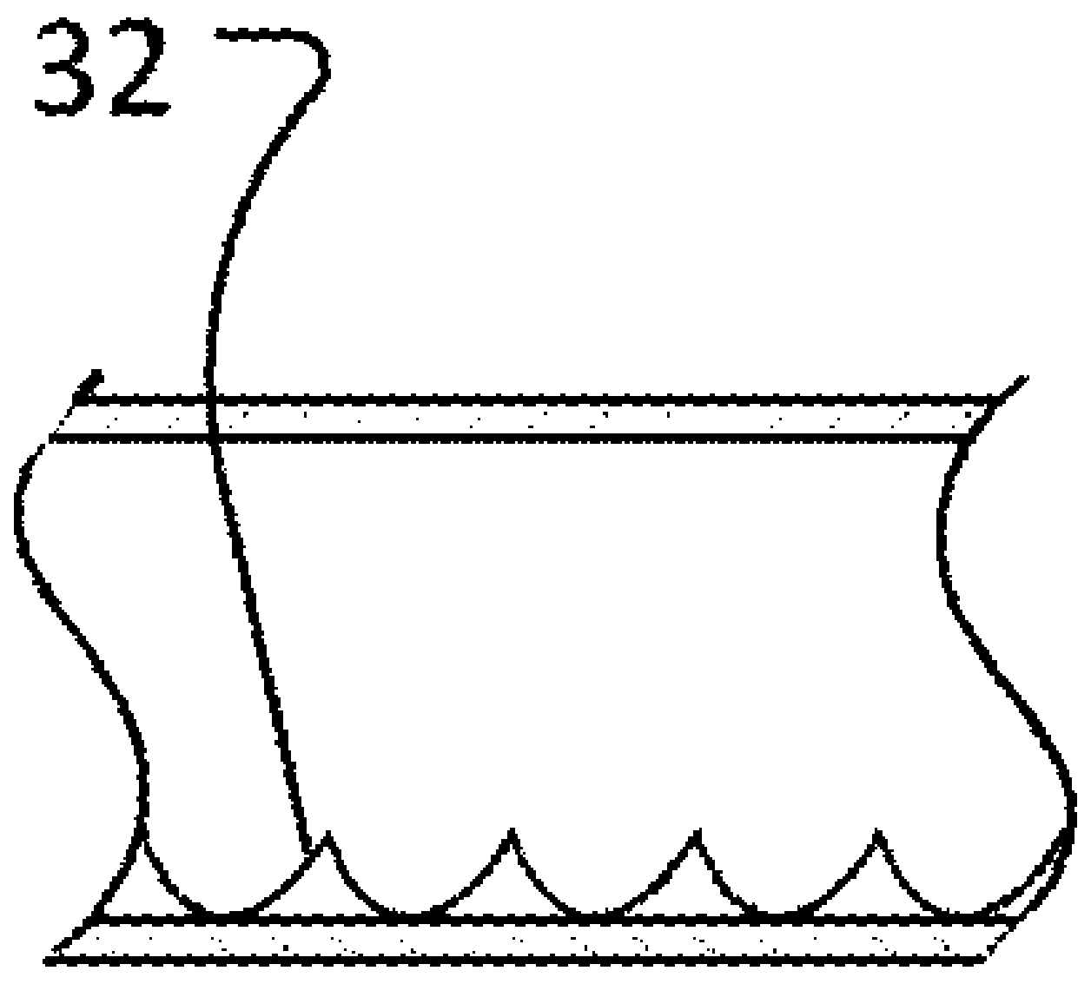

Fig. 4D

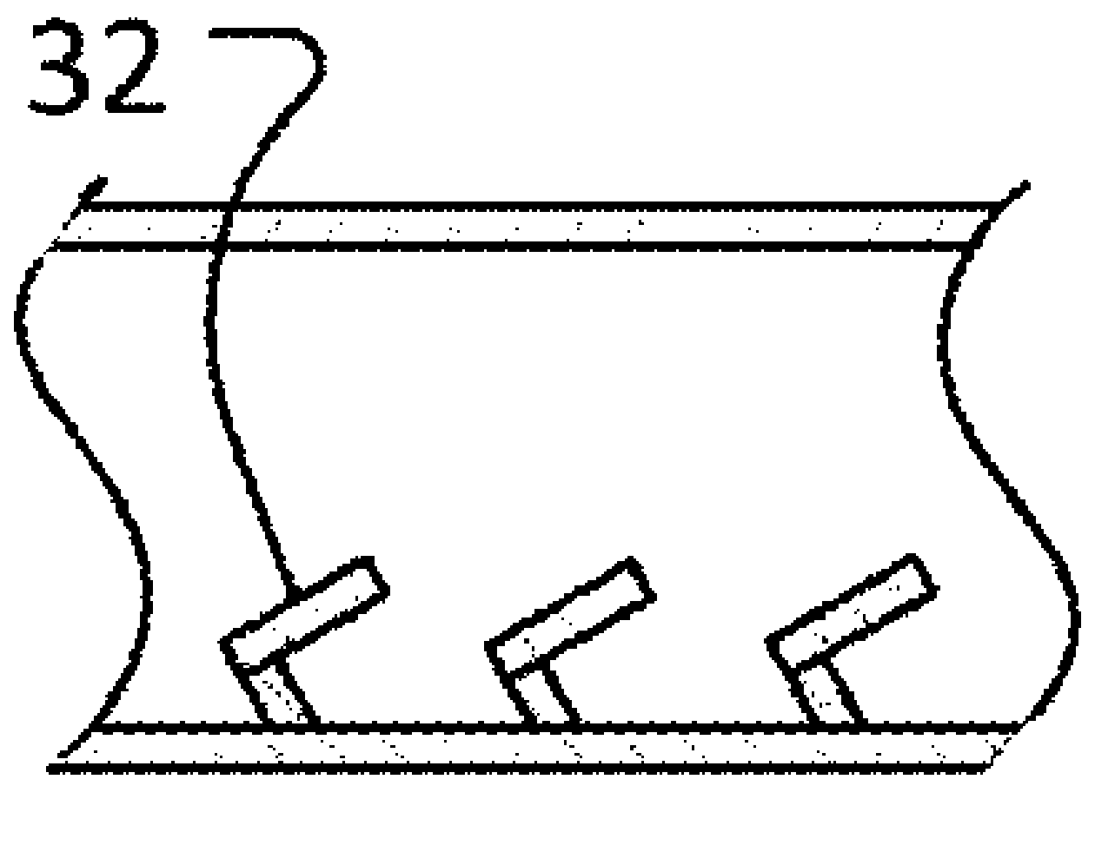

Fig. 4E

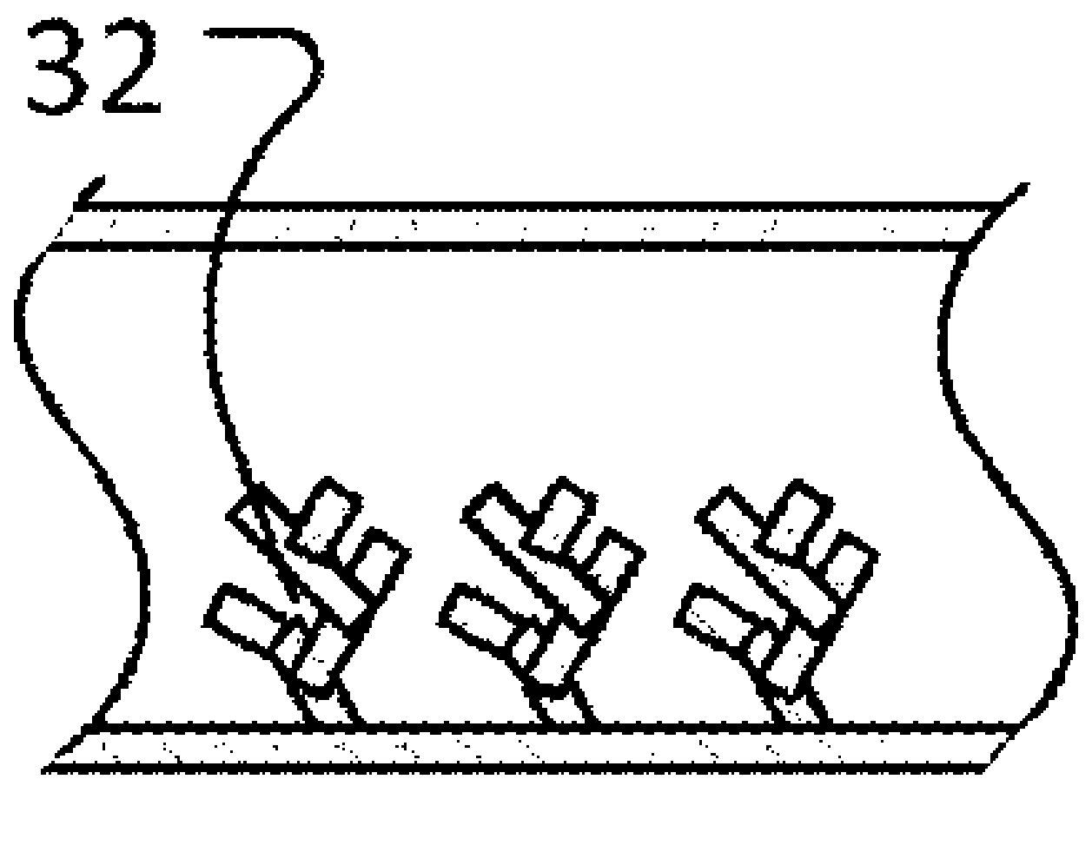

Fig. 4F

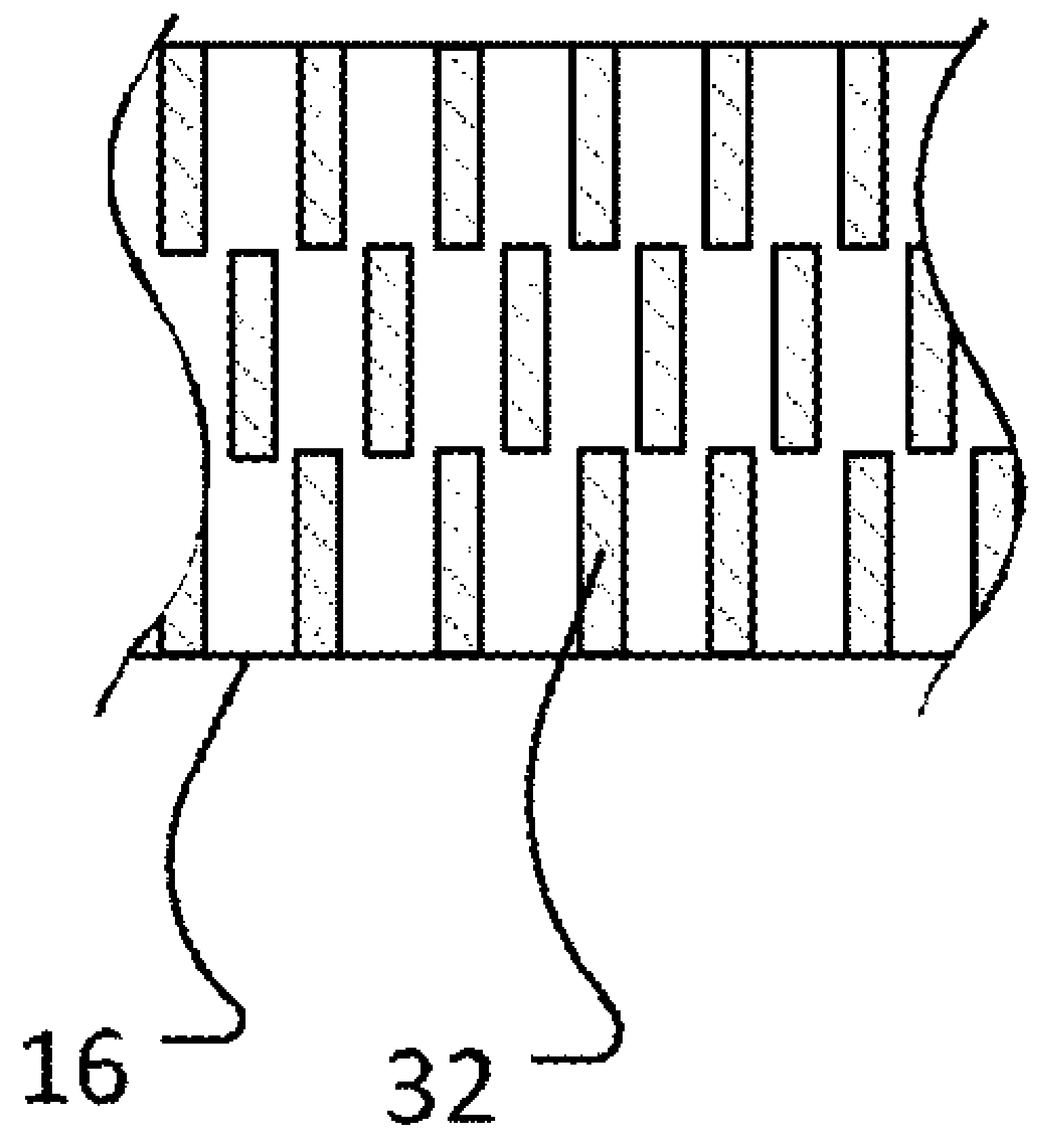

Fig. 5A

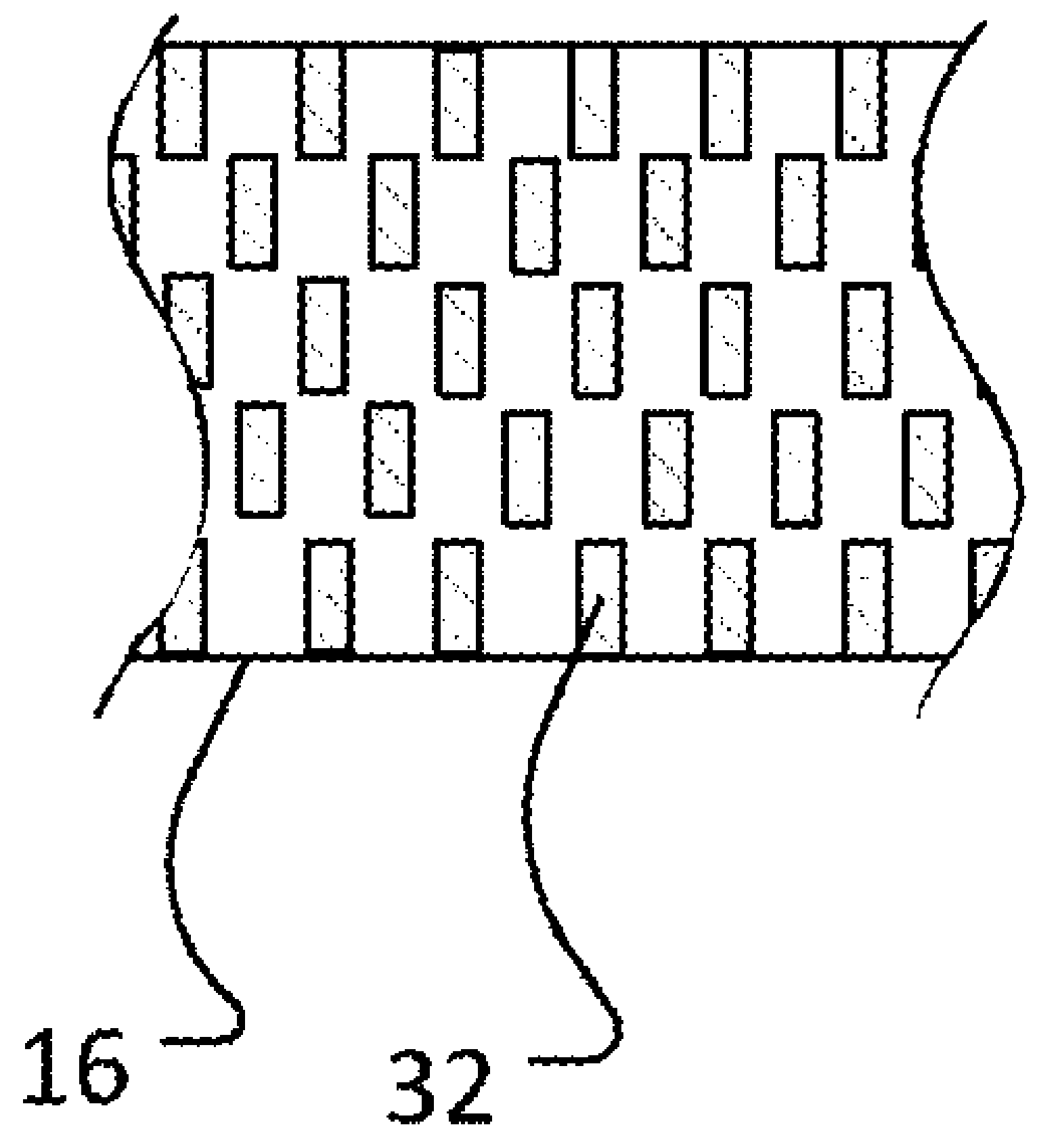

Fig. 5B

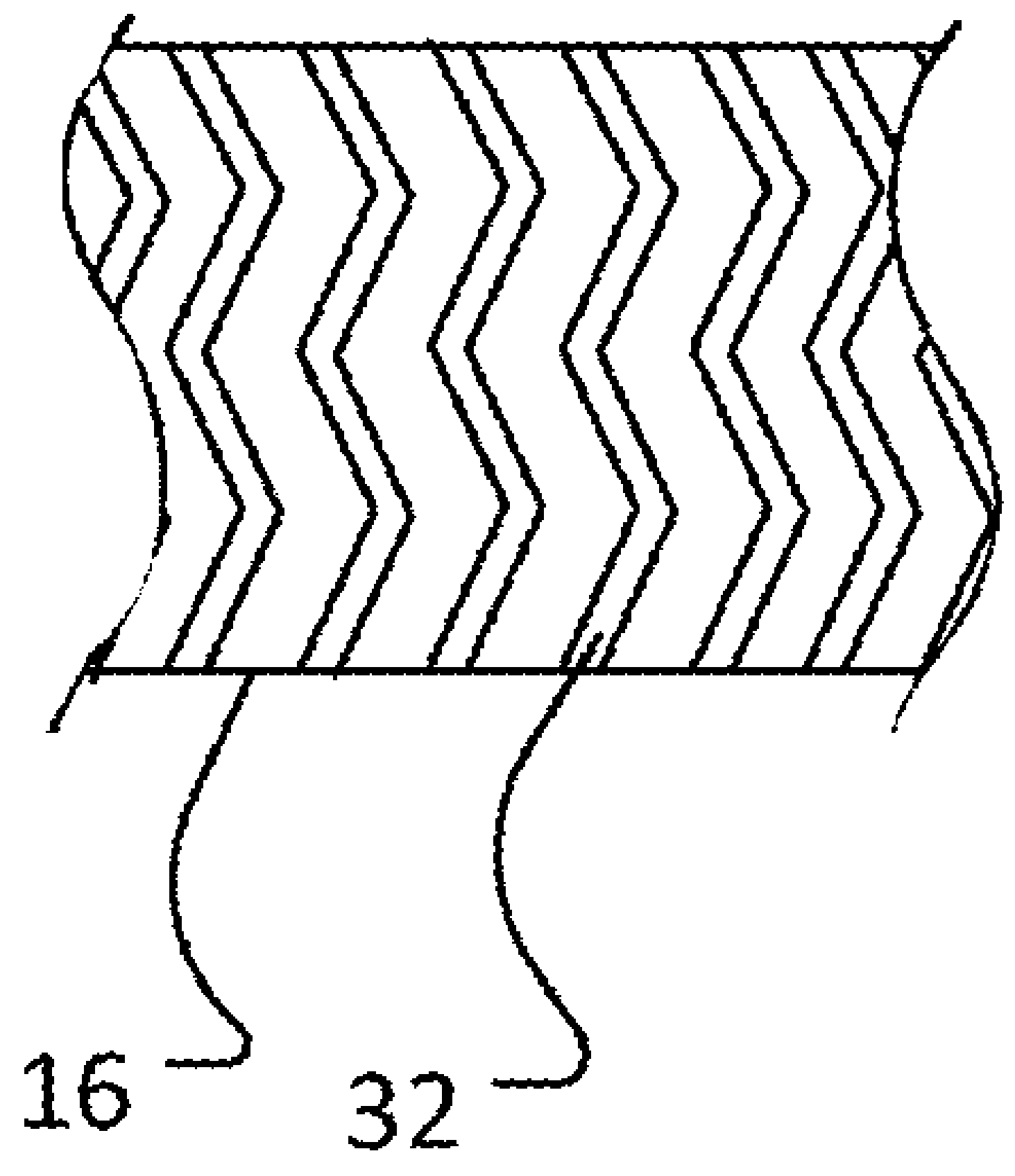

Fig. 5C

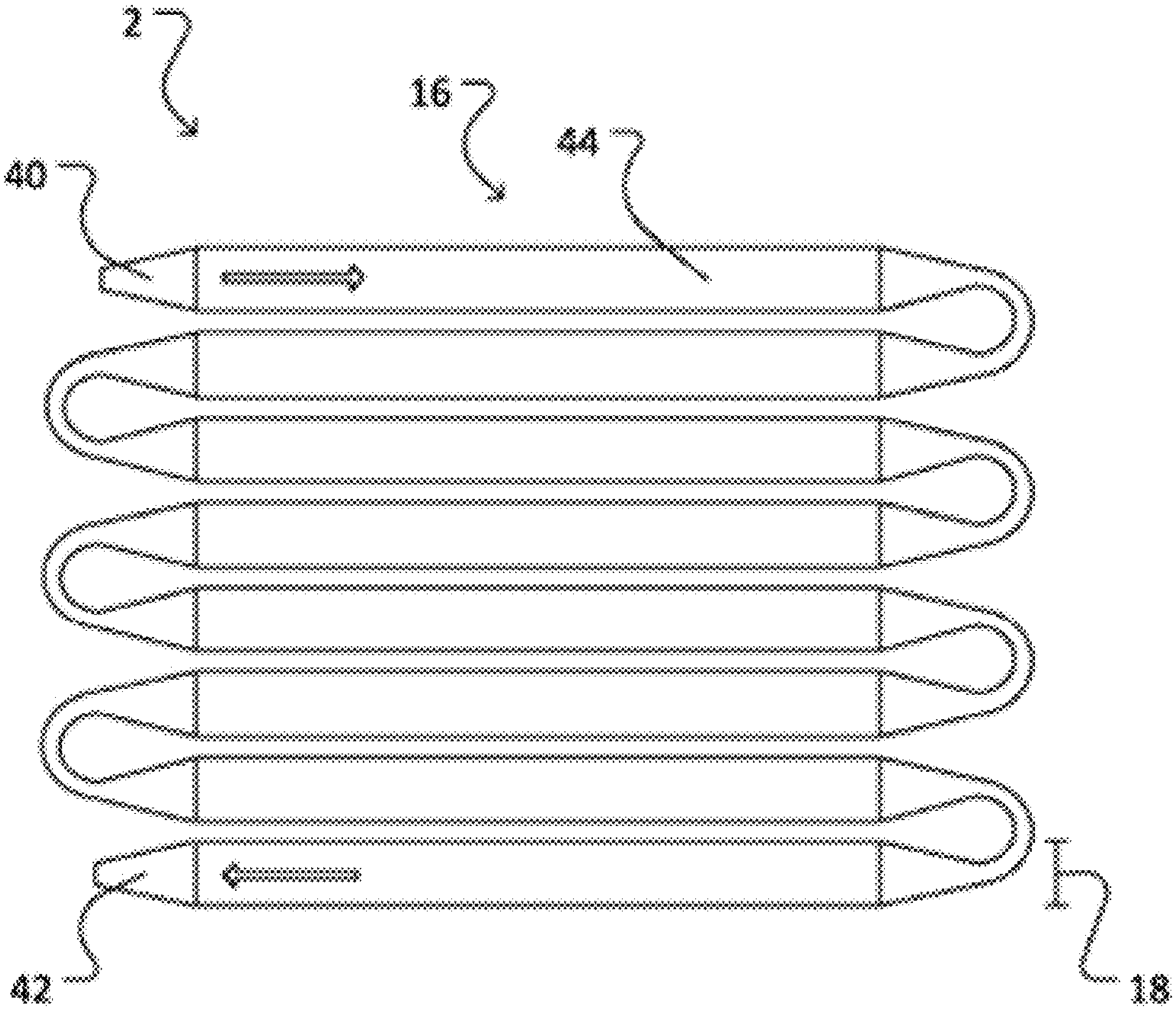

Fig. 6A

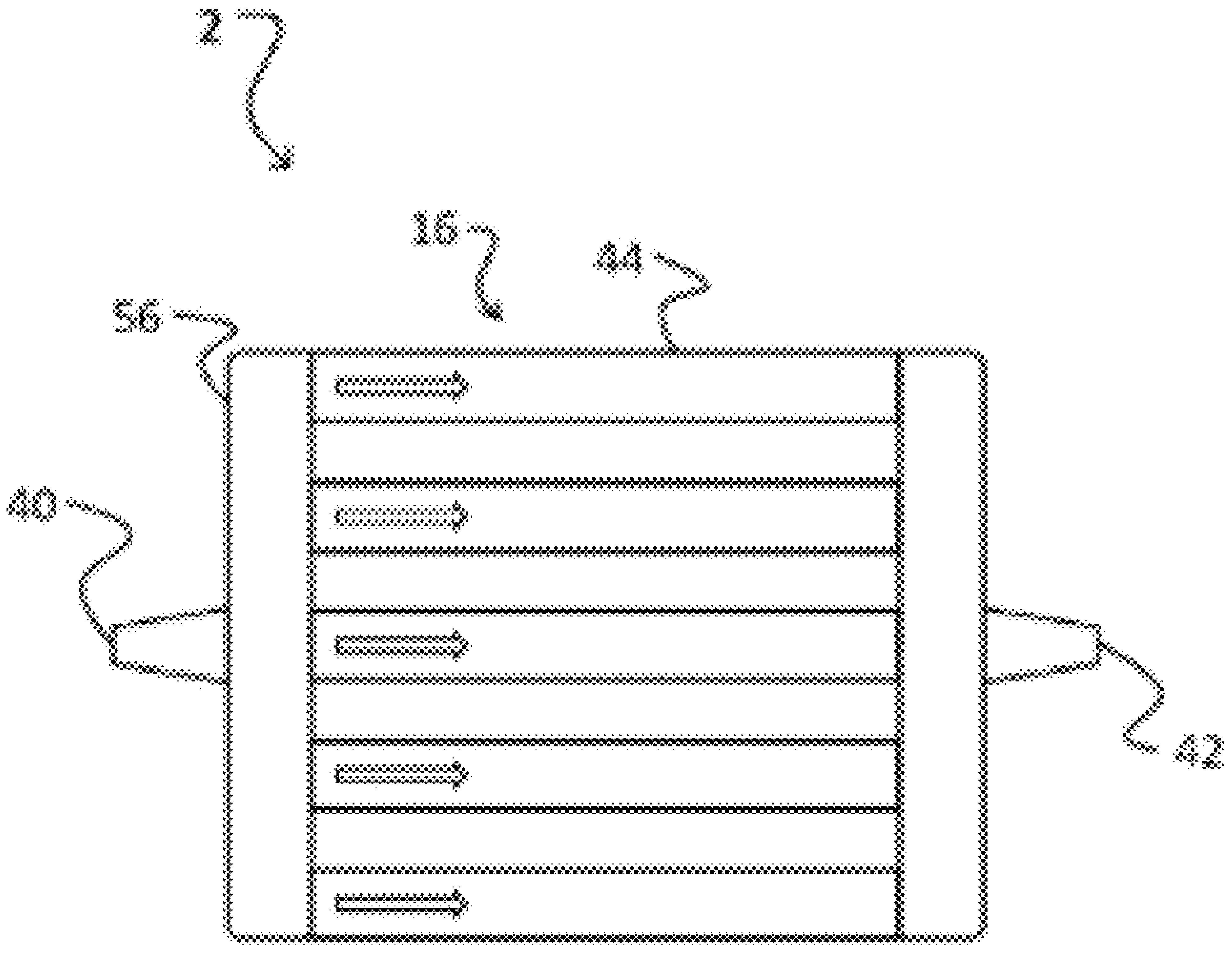

Fig. 6B

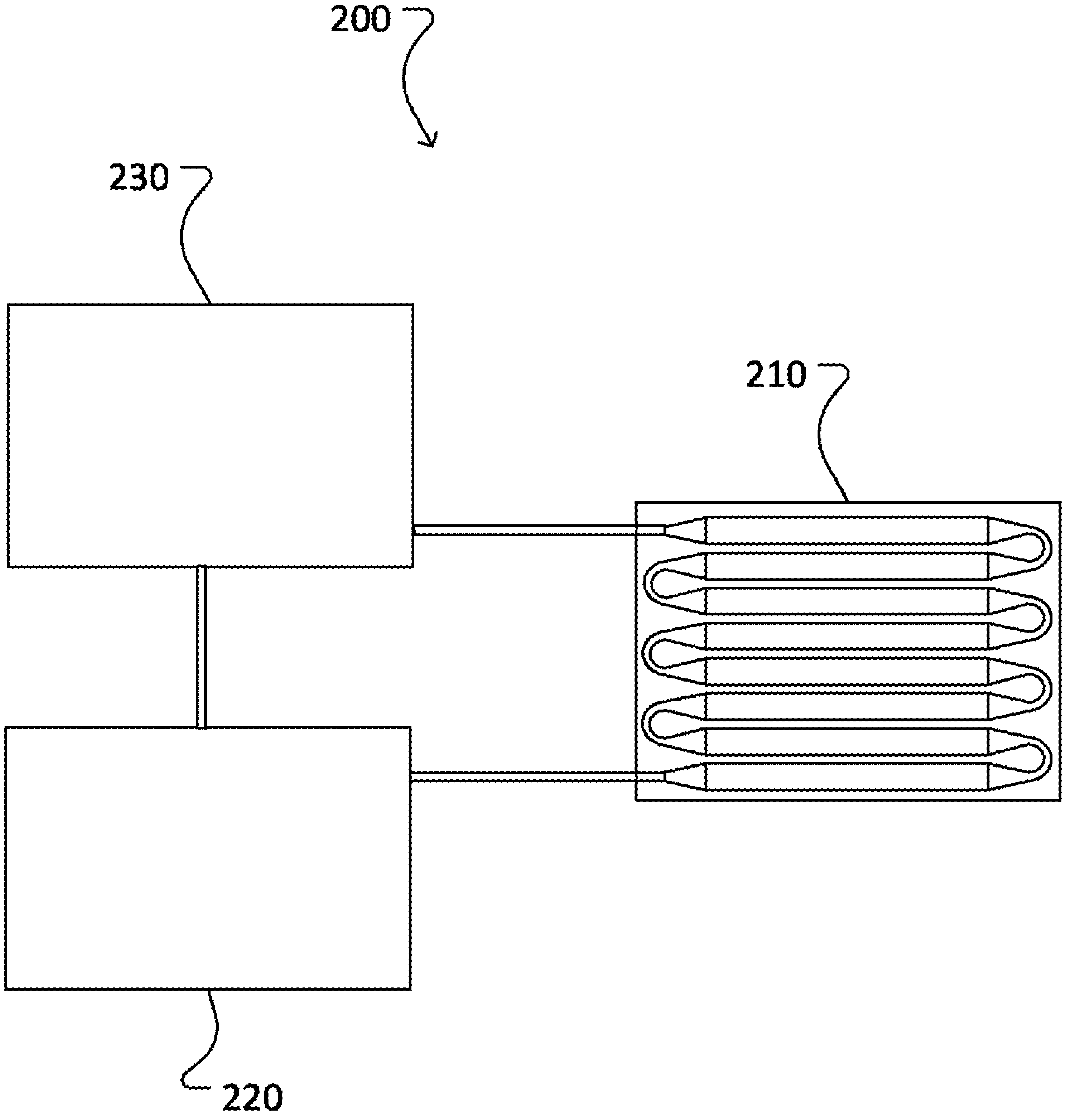

Fig. 7

METAL-AIR FUEL CELL

CROSS REFERENCE TO RELATED APPLICATIONS

This is a division of U.S. patent application Ser. No. 15/923,256, entitled "METAL-AIR FUEL CELL", filed Mar. 16, 2018, which is a continuation of PCT application No. PCT/CA2016/051080, entitled "METAL-AIR FUEL CELL", filed Sep. 13, 2016, which are both incorporated herein by reference. PCT/CA2016/051080 is a PCT application based upon U.S. provisional patent application Ser. No. 62/219,984, entitled "METAL-AIR FUEL CELL", filed Sep. 17, 2015, which is also incorporated herein by reference.

BACKGROUND OF THE INVENTION

Technical Field

This invention relates to metal-air fuel cells, such as zinc-air fuel cells.

Background

Metal-air fuel cells provide high energy efficiency and yet are low cost with low environmental impact. The zinc-air fuel cell is an example of a metal-air fuel cell. In a zinc air fuel cell, zinc metals are provided as fuel, air is provided as an oxygen source, and an aqueous alkaline solution, such as potassium hydroxide (KOH), is provided as an electrolyte. When an electric circuit is closed, the anode consumes zinc metal via the anode or negative electrode reaction,

$$Zn+4KOH\rightarrow K_2Zn(OH)_4+2K^++2e \qquad (1)=-1.216\ V$$

Zinc metal is consumed as it reacts with potassium hydroxide, potassium zincate is formed ($K_2Zn(OH)_4$) and electrons are released to an anode current conductor.

Oxygen is supplied to the cathode and reacts with H_2O and electrons on the cathode to form hydroxyl ions (OH^-). The cathode or positive electrode reaction is therefore,

$$\tfrac{1}{2}O_2+H_2O+2e\rightarrow 2OH\text{—} \qquad (2)\ E^0=0.401\ V$$

The hydroxyl ions from equation (2) and the potassium ions from equation (1) then react with zinc metal again in equation (1) at the anode.

According to this reaction scheme, the oxidation of zinc and the reduction of oxygen cause the change of chemical energy into electrical energy. For the reactions to proceed over long times there must be a continuous supply of zinc metal and air as well as a means of constant flow of electrons from the system, i.e., connection to a load.

In previous zinc-air implementations the metal electrodes have had a fixed quantity of zinc, limiting their available energy and having rechargeability drawbacks due to size augmentation of the electrodes upon cycling. Decreases in the electrode area leads to a decrease in power of the fuel cell system.

Improved metal-air fuel cells are desirable.

SUMMARY OF THE INVENTION

The inventions described herein have many aspects, some of which relate to fuel cells, fuel cell stacks, metal-air fuel cell system, and methods of charging metal-air fuel cells.

In one aspect a fuel cell is provided. The fuel cell comprises: a cathode; an anode comprising an anode chamber and an anode current collector, the anode chamber at least partially defined by the anode current collector; and a cathode chamber at least partially defined by the cathode. The anode chamber comprises one or a plurality of anode flow channels for flowing an electrolyte in a downstream direction.

The anode current collector may comprise a plurality of particle collectors projecting into the anode chamber to collect particles suspended in the electrolyte.

In another aspect, a method of charging a metal-air fuel cell is provided. The method includes a step of orienting an anode chamber horizontally. A corresponding anode current collector is positioned below the anode chamber. The anode current collector includes a plurality of particle collectors projecting into the anode chamber. The method further method includes a step of providing metal particles suspended in an electrolyte to flow through the anode chamber in a downstream direction oriented horizontally. The method further method includes a step of allowing a bed of the metal particles to form on the anode current collector. The plurality of particle collectors perturb the flow of electrolyte through the anode chamber and encourage settling of the particles one of on and between the particle collectors. The method further method includes a step of maintaining uniform formation of the bed.

The plurality of particle collectors may be configured to perturb the flow of electrolyte through the anode chamber and encourage settling of the particles on or between the particle collectors.

The particle collector may comprise a laterally elongated member. The laterally elongated member may extend up to a width of the anode flow channel. The angle defined between the laterally elongated member and a planar portion of the anode current collector in the upstream direction may be between 10 to 90 degrees, or 20 to 80 degrees, or 30 to 70 degrees, or 90 to 120 degrees, or 120 to 180 degrees. The height of the laterally elongated member relative to the planar portion of the anode current collector may range from 0.2 mm to 5.0 mm, or 0.5 to 3.0 mm, or 1.0 to 2.0 mm. The ratio of (i) a height of the laterally elongated member relative to the planar portion of the anode current collector and (ii) a height of the anode chamber may range from 0.1 to 0.6, or 0.2 to 0.5, or 0.3 to 0.4.

The number of the particle collectors per linear centimeter may range from 0.5 to 10, or 1 to 5, or 1 to 2. The distance between adjacent particle collectors may be less than a height of the particle collector relative to a planar portion of the anode current collector. The plurality of particle collectors may be arranged in an array configured to form a uniform bed of the particles on the anode current collector.

The anode chamber may comprise a parallel flow configuration or a serpentine flow configuration. The anode flow channels may comprise length to width ratios in the ranges of 50:1 to 2:1, 25:1 to 4:1, or 10:1 to 5:1. The width of the anode flow channels may range from 2 mm to 20 cm, 5 mm to 10 cm, or 1 cm to 5 cm.

The cathode and anode current collector may be planar. The surface area of the anode current collector may range from 1 cm^2 to 1 m^2.

The height of an electrolyte flow field within the anode chamber may be 0.5 mm to 4 mm, 1 mm to 3 mm, or 2 mm.

The fuel cell may be a zinc-air fuel cell and the particles may be zinc particles. The electrolyte may be potassium hydroxide.

According to another aspect, a fuel cell stack is provided. The fuel stack comprising a plurality of fuel cells as described herein. The plurality of fuel cells may be oriented horizontally and stacked on top of one another to form the fuel cell stack, or may be oriented vertically and stacked beside one another to form the fuel cell stack.

According to another aspect, a metal-air fuel cell system is provided. The metal-air fuel cell system comprises: a fuel cell as described herein; a metal electrolyzer comprising in fluid communication with an outlet of the fuel cell; and a tank in fluid communication with an outlet of the metal electrolyzer and an inlet of the fuel cell. The fuel cell may be a zinc-air fuel cell and the metal electrolyzer may be a zinc electrolyzer.

According to another aspect, a method of charging a metal-air fuel cell is provided. The method comprises:

(a) orienting an anode chamber horizontally wherein a corresponding anode current collector is positioned below the anode chamber;

(b) providing metal particles suspended in an electrolyte to flow through the anode chamber;

(c) allowing a bed of the metal particles to form on the anode current collector; and

(d) maintaining uniform formation of the bed.

Step (c) may comprise one or more of:

(i) maintaining the flow of the metal particles suspended in the electrolyte at a predetermined flow rate;

(ii) periodically stopping the flow of the metal particles suspended in the electrolyte;

and

(iii) providing a plurality of particle collectors on the anode current collector.

Step (d) may comprise providing a uniform flow of the electrolyte through the anode chamber. Providing the uniform flow may comprise providing a continuous pressure drop in a downstream direction in the anode chamber and a minimal pressure drop in a direction normal to the downstream direction. Providing the continuous pressure drop in the downstream direction and the minimal pressure drop in the direction normal to the downstream direction may comprise providing a parallel or serpentine flow path for the anode chamber. Providing the parallel or serpentine flow path may comprise providing channels for the parallel or serpentine flow path defined by a length to width aspect ratio of 50:1 to 2:1, 25:1 to 4:1, or 6:1 to 5:1.

Step (c) may comprise forming the bed to a depth of 0.2 mm to 2.0 cm, or 1 mm to 1.0 cm, or 2 mm to 4 mm, or 0.5 mm to 2 mm. Step (c) may comprise forming the bed to a depth wherein a ratio of the depth to a height of the anode chamber ranges from 0.1 to 0.6, or 0.2 to 0.5, or 0.3 to 0.4.

Step (b) may comprise providing metal particles ranging in size from 5 nm to 1 mm, 5 nm to 0.5 mm, or 5 nm to 0.3 mm.

The flow velocity of the electrolyte in the anode chamber may range from 1 cm^3/s to 5000 cm^3/s. The flow rate of the electrolyte in the anode chamber may range from 1 L/min. to 7 L/min, or 3 L/min. to 7 L/min or 3 L/min. to 5 L/min.

The gauge pressure of the electrolyte in the anode chamber may range from 0.69 kPa to 103.4 kPa, or from 13.8 kPa to 68.9 kPa. The pressure drop traversing the anode chamber may be less than 103.4 kPa.

The metal particles may be zinc particles, and the electrolyte may be aqueous potassium hydroxide. The concentration of potassium hydroxide may be 5% to 60% by weight, or 20% to 50% by weight, or 30% to 45% by weight.

The method may comprise drawing a current density of 50 mA/cm^2 or more from the fuel cell. The method may comprise applying a load to the fuel cell and discharging for a period of 1 to 20 hours.

The foregoing discussion merely summarizes certain aspects of the inventions and is not intended, nor should it be construed, as limiting the inventions in any way.

BRIEF DESCRIPTION OF THE DRAWINGS

The above-mentioned and other features and advantages of this invention, and the manner of attaining them, will become more apparent and the invention will be better understood by reference to the following description of embodiments of the invention taken in conjunction with the accompanying drawings, wherein:

FIG. **1**A is a partial cutaway side view of a fuel cell according to an embodiment of the invention;

FIG. **1**B is a partial cutaway side view, perpendicular to the view shown in FIG. **1**A, of the embodiment shown in FIG. **1**A;

FIG. **2** is a close up partial cutaway side view of the embodiment shown in FIG. **1**A;

FIG. **3** is a partial top view of an anode chamber according to an embodiment of the invention;

FIGS. **4**A to **4**F are partial cutaway side views of various embodiments of the invention;

FIGS. **5**A to **5**C are partial top views of various anode chambers according to embodiments of the invention;

FIG. **6**A is a top view of a fuel cell according to an embodiment of the invention;

FIG. **6**B is a top view of a fuel cell according to an embodiment of the invention; and

FIG. **7** is a schematic view of a metal-air fuel cell system according to an embodiment of the invention.

Corresponding reference characters indicate corresponding parts throughout the several views. The exemplifications set out herein illustrate embodiments of the invention and such exemplifications are not to be construed as limiting the scope of the invention in any manner.

DETAILED DESCRIPTION OF THE INVENTION

Throughout the following description, specific details are set forth in order to provide a more thorough understanding of the invention. However, the invention may be practiced without these particulars. In other instances, well known elements have not been shown or described in detail to avoid unnecessarily obscuring the invention. Accordingly, the specification and drawings are to be regarded in an illustrative, rather than a restrictive, sense.

A number of directional conventions are employed in this specification to help clarify their meaning, as follows:

“upstream” and “downstream” as used herein relate to directions, orientations, positions or arrangements of features relative to the flow of electrolyte from the inlet of the anode chamber to the outlet of anode chamber, wherein relative to a first position within the anode chamber from the inlet of the anode chamber, a second position in the anode chamber closer to the inlet along the flow path of the electrolyte is “upstream”, and a third position within the anode chamber further away from the inlet along the flow path of the electrolyte is “downstream”;

“lateral, “laterally” and the like as used herein relates to the directions normal to the flow of electrolyte from the inlet of the anode chamber to the outlet of anode chamber or from the inlet of an anode channel to the outlet of an anode channel;

- "horizontal" and "horizontally" as used herein refers to an orientation parallel to the ground; and
- "top", "bottom", "above" and "below" as used herein refer to the orientations, positions or arrangements of features when the anode chamber is oriented substantially horizontally.

The term "fuel cell" as used herein refers to an electrochemical device as would be understood by a person skilled in the art. The term "fuel cell" includes, without limitation, devices known as "flow batteries" and similar terminology.

The term "uniform" as used herein with reference to an anode bed refers to an anode bed with an substantially even distribution of metal particles.

The term "substantially" as used herein refers to the complete or nearly complete extent or degree of an action, characteristic or result. For example, a "substantially" continuous pressure drop would mean that the pressure drop is either completely continuous or nearly completely continuous. The exact allowable degree of deviation from absolute completeness may in some cases depend on the specific context. However, generally speaking the nearness of completion will be so as to have the same overall result as if total completion were obtained. The use of "substantially" is equally applicable when used in a negative connotation to refer to the complete or near complete lack of an action, characteristic or result. For example, "substantially" no pressure drop refers to either a complete lack of pressure drop, or a lack of pressure drop so nearly complete that the effect would be the same as if there was no pressure drop. In other words, "substantially" no pressure drop means that there may still be a measurable pressure drop as long as there is no measurable effect thereof.

Conventional anode beds for zinc-air fuel cells are formed by one of two approaches. One approach is to form a dense bed of packed zinc particles where the electrolyte is forced to flow through the bed at high pressure. The inventors have determined at least two drawbacks with this approach. First, the amount of pressure that can be mechanically tolerated by a fuel cell limits the pumping pressure to below about 68948 Pa since higher pressures would place too much mechanical stress on the fuel cell. Second, reducing pumping pressure limits the range of particle sizes that can be used. A pumping pressure below 68948 Pa is only useful in an anode bed where the mean particle size is above 200 microns; using smaller particles would require pumping pressures that are too high, e.g. as high as 689476 Pa, in order to maintain sufficient zinc dissolution reactions.

An alternative approach is to pump a slurry or suspension of zinc particles through the anode chamber. In the absence of a packed particle bed the pumping pressures are much lower, for example lower than 55.2 kPa. However with this approach, the inventors have determined that the particles make only transient contact with the anode current collector, and the current density generated is therefore limited by the number of transient contacts that are formed at any instant.

Claims of the present invention relate to high energy efficiency metal-air fuel cells. In one embodiment, a fuel cell with a substantially horizontally-oriented anode chamber is provided. Small metal particles, such as in the range of 15 nm to 300 microns, suspended in electrolyte are pumped into the anode chamber at low pressure, such as below 68.9 kPa. A dense bed of the metal particles is formed on an anode current collector at low electrolyte pressures by gravitational settling and one or more of: controlling the electrolyte flow rate; intermittently stopping the electrolyte flow; and providing particle collectors on the anode current collector. The advantages of this approach include low electrolyte pressure (to reduce pumping energy costs and mechanical stress) and small metal particle size (to increase electrical current generation), which are made possible by the anodic reaction occurring along the top of the anode bed, as well as through the anode bed. At any moment, more metal particles are in contact with each other and with the anode current collector. Thus the total surface area of metal particles contributing to the electrode reaction and generation of electrical current is much greater, in turn leading to higher energy efficiency. Electrolyte flow along and through the anode bed also removes oxidized metal reaction products from the reaction site.

FIG. **1**A shows part of a fuel cell stack **10** according to one embodiment of the invention. Fuel cell stack **10** is comprised of a plurality of vertically stacked fuel cells. FIG. **1**A shows a first fuel cell **2**, and part of an identical, partial second fuel cell **2'** below fuel cell **2**. In some embodiments the fuel cell stack may only comprise a single fuel cell. In some embodiments, such as in fuel cell stack **10**, the fuel cells are oriented horizontally and stacked on top of one another to form a fuel cell stack. In some embodiments, the fuel cells are oriented vertically and stacked beside one another to form a fuel cell stack. FIG. **1**B shows the alternate side view of fuel cell stack **10** as seen perpendicular to FIG. **1**A.

Fuel cell **2** of fuel cell stack **10** includes a cathode chamber **12**, cathode **14**, anode chamber **16**, anode current collector **18** and a separator **20**. The section of fuel cell **2'** of fuel cell stack **10** shown in FIG. **1**A includes cathode chamber **12'**, cathode **14'**, and anode chamber **16'**. Separator **20** prevents electrical contact between the cathode **14** and the anode chamber **16** but allows for ionic conductivity between the two. A contact pin **22'** electrically connects anode current collector **18** to cathode **14'** to close the circuit. In an alternate arrangement contact pin **22'** and anode current collector **18** are integrally formed. The components of fuel cell **2** of fuel cell stack **10** will be described in greater detail herein but it will be understood that the features and functions of the components of other fuel cells of fuel cell stack **10**, including fuel cell **2'**, will correspond to those of the components of fuel cell **2**.

Suitable construction and configuration of cathode chamber **12** and cathode **14**, as known in the art, are provided to extract oxygen from air flowing through cathode chamber **12** (direction of air flow represented by arrow **24**) by electrochemical reduction of oxygen at cathode **14**, and to allow migration of formed hydroxide into anode chamber **16** (direction of oxygen extraction/reduction and hydroxide ion migration represented by arrow **26**). In some embodiments, such as in fuel cell stack **10**, cathode **14** is generally planar.

Anode chamber **16** is shaped to permit metal particles **30** suspended in an electrolyte to flow therethrough in a downstream direction as represented by arrow **28**. In some embodiments, the metal particles may be zinc, aluminum, beryllium, calcium, iron, lithium, magnesium, sodium, titanium, or a mixture of such metals. In the illustrated embodiment, metal particles **30** are zinc particles. In some embodiments, the metal particles may range in size from 5 nm to 1 mm, or 5 nm to 0.5 mm, or 5 nm to 0.3 mm.

In some embodiments, the electrolyte may be alkaline, such as an aqueous alkali hydroxide. In some embodiments, the aqueous alkali hydroxide may be aqueous potassium hydroxide or aqueous sodium hydroxide. In some embodiments, the concentration of the aqueous alkali hydroxide may range from 5% to 60% by weight, or 20% to 50% by weight, or 30% to 45% by weight. In other embodiments, the electrolyte may be non-alkaline.

In some embodiments, such as in fuel cell **2**, anode current collector **18** is made of a material with high conductivity and high stability in aqueous alkaline solutions. In example embodiments, the anode current collector may be stainless steel, nickel, iron, titanium, copper, gold, silver, magnesium, indium, lead, or carbon. In other embodiments alloys or conductive oxides of combinations of these and other elements are employed. In some embodiments, anode current collector **18** is generally planar. Anode current collector **18** is disposed opposite of cathode **14** with anode chamber **16** at least partially defined therebetween. In some embodiments, the surface area of each of cathode **14** and anode current collector **18** may range from 1 cm' to 1 m^2. In an example embodiment, the surface area of cathode **14** and anode current collector **18** are each about 500 cm^2 and separated by about 3 mm.

In some embodiments, such as in fuel cell **2**, anode current collector **18** includes a plurality of particle collectors **32** projecting into anode chamber **16**. Particle collectors **32** may be of any shape and configuration suitable for collecting particles **30** suspended in the electrolyte and flowing through anode chamber **16**. In some embodiments, particle collectors **32** are of suitable size, shape, configuration and/or array for trapping particles **30** and facilitating their formation into an anode bed **34** on anode current collector **18**. In some embodiments, particle collectors **32** are of suitable size, shape, configuration and/or array for establishing a series of obstacles that perturb the flow of electrolyte through anode chamber **16** and encourage the settling of particles on or between the particle collectors. FIGS. **4**A to **4**F show non-limiting examples of side views of other possible shapes of particle collectors **32**. In some embodiments particle collectors **32** may be porous, or have holes, slits, and the like to enhance circulation of electrolyte. In a particular embodiment, particle collectors **32** are formed from a conductive mesh. The mesh should limit pore sizes to a suitable size, shape, configuration and/or array to facilitate trapping particles.

In a particular embodiment particle collectors **32** are constructed of the same conductive material as anode current collector **18**. In other embodiments particle collectors **32** may be constructed of a different conductive material or non-conductive material. In a particular embodiment, particle collectors **32** are integrally formed with anode current collector **18**. In other embodiments particle collectors **32** may be formed separately and then coupled to anode current collector **18**. In some embodiments the surface of anode current collector **18** is provided with sufficient particle collectors **32** to form a uniform anode bed **34**.

As shown in FIG. **2**, each particle collector **32** at least partially defines an opening **35** for receiving particles **30** flowing downstream through anode chamber **16**. In some embodiments, such as in fuel cell **2**, opening **35** may face a generally upstream or downstream direction. Each particle collector **32** also at least partially defines a pocket or well **37** shaped to accumulate trapped particles **30** therein. Opening **35** is in fluid communication with well **37**. In some embodiments, such as in fuel cell **2**, opening **35** defines an opening of well **37**. The size of opening **35** and well **37** may be partly defined by an angle **38** defined between particle collector **32** and a planar portion of anode current collector **18** in the upstream direction. In some embodiments, angle **38** may be between 5 to 90 degrees, or 20 to 70 degrees, or 30 to 60 degrees. In some embodiments, angle **38** may be between 90 to 120 degrees, or 120 to 180 degrees.

As shown in FIG. **3**, anode chamber **16** may be subdivided into a plurality of substantially parallel anode channels **44** separated by internal walls **48**. In the embodiment shown in FIGS. **1** to **3**, particle collector **32** is a laterally-elongated scoop. In some embodiments, the lateral width W_{pc} of each scoop **32** extends up to a width W_{ac} of anode channel **44**. In some embodiments, the number of particle collectors **32** per linear centimeter (in the upstream/downstream direction) ranges from 0.5 to 10, or 1 to 5, or 1 to 2. In some embodiments, electrolyte in adjacent channels may flow in the same direction. In other embodiments, electrolyte in adjacent channels may flow in opposite directions.

In some embodiments, the particle collector **32** features are microscopic and can be considered simply as an increase in surface roughness of the anode channels **44**. The increase in surface roughness as compared to a smooth planar surface ranges from 4:1 to 10,000:1, or 10:1 to 1000:1, or 50:1 to 500:1.

In some embodiments, particle collectors **32** may be arranged in a staggered array or other repeating or random array that facilitates formation of a uniform anode bed **34** and does not interfere with uniform flow of electrolyte. FIGS. **5**A to **5**C show non-limiting examples of top views of other possible configurations of particle collectors **32**.

As shown in FIG. **2**, the height H_{pc} of particle collector **32** is limited to a height that does not significantly impede the flow of electrolyte through anode chamber **16**. In some embodiments, height H_{pc} relative to the planar portion of anode current collector **18** ranges from 0.2 mm to 5.0 mm, or 0.5 to 3.0 mm, or 1.0 to 2.0 mm. In some embodiments, a ratio of height H_{pc} to the height of the anode chamber **16** (H_{ac}) ranges from 0.1 to 0.6, or 0.2 to 0.5, or 0.3 to 0.4.

The formation of anode bed **34** is controlled (as described further below) to ensure it does not significantly impede the flow of electrolyte through anode chamber **16**. In some embodiments the depth D_{ab} of anode bed **34** does not exceed the height H_{pc} of particle collectors **32**. In some embodiments anode bed **34** may have a depth D_{ab} ranging from 0.2 mm to 20 mm, or 1 mm to 10 mm, or 2 mm to 4 mm, or 0.5 mm to 2 mm, and in some embodiments anode bed **34** may have a depth D_{ab} wherein a ratio of depth D_{ab} to a height of the anode chamber H_{ac} ranges from 0.1 to 0.6, or 0.2 to 0.5, or 0.3 to 0.4. In some embodiments, depth D_{ab} is uniform across most or all of anode bed **34**.

As shown in FIG. **6**A, anode chamber **16** includes an inlet **40**, an outlet **42**, and a plurality of channels **44** linked in a serpentine manner. In some embodiments, each channel **44** is dimensioned to facilitate uniform flow of electrolyte therethrough characterized by a substantially continuous pressure drop of electrolyte in the direction of electrolyte flow and substantially no pressure drop in the lateral direction. In some embodiments, each channel **44** has a length to width aspect ratio of 50:1 to 2:1, 25:1 to 4:1, or 10:1 to 5:1.

In some embodiments channels **44** may be arranged in other configurations, such as in a parallel flow configuration as shown in FIG. **6**B. Anode chamber **16** includes an inlet **40**, an outlet **42**, and a plurality of channels **44** linked in a parallel manner. In some embodiments, each channel **44** is dimensioned to facilitate uniform flow of electrolyte therethrough characterized by a substantially continuous pressure drop of electrolyte in the direction of electrolyte flow and substantially no pressure drop in the lateral direction. In some embodiments, each channel **44** has a length to width aspect ratio of 50:1 to 2:1, 25:1 to 4:1, or 10:1 to 5:1. A manifold **56** is used to facilitate distribution amongst parallel flow channels.

In some embodiments, other configuration of channels **44** can be formed as combinations of serpentine and parallel flow channels.

In operation, when electricity is required, metal particles **30** suspended in electrolyte are loaded into anode chamber **16** and air is loaded into cathode chamber **14**. A uniform bed of metal particles **30** is controllably formed on anode current collector **18** by one or more of the following mechanisms: (i) maintaining the flow of metal particles **30** suspended in the electrolyte at a predetermined flow rate slow enough to allow some metal particles **30** to settle onto anode current collector **18**; (ii) periodically stopping the flow of metal particles **30** suspended in the electrolyte to allow some metal particles **30** to settle onto anode current collector **18**; and (iii) providing a plurality of particle collectors **32** as described herein on anode current collector **18** to collect metal particles **30**. In some embodiments, for each of the foregoing mechanisms anode chamber **16** is oriented substantially horizontally to allow particles **30** to settle by gravity to form anode bed **34** on anode current collector **18**.

Particles **30** of anode bed **34** are therefore in contact with anode current collector **18** and/or with other particles **30** in anode bed **34**. The particles **30** along the top of anode bed **34** then undergo the anodic reaction. The anodic reaction occurs principally at the top of anode bed **34**, and decreases in a direction downwards towards anode current collector **18**.

Electrolyte flows over anode bed **34**, in direct contact with particles **30**, to allow the anodic reaction to occur. Electrolyte flowing to the reaction site also removes oxidized metal product (e.g. potassium zincate). Since electrolyte does not need to flow through anode bed **34** for the anodic reaction to occur, (i) lower electrolyte pressures may be used to lower pumping energy costs and reduce mechanical stress on fuel cell **2** and/or (ii) smaller metal particles **30** may be used to increase efficiency without increasing electrolyte pressure or decreasing the electrolyte flow rate. In some embodiments, the size of metal particles **30** may range from 5 nm to 1 mm, 5 nm to 0.5 mm, or 5 nm to 0.3 mm. Electrolyte flows principally across the top of the bed of zinc particles but some flow will penetrate into the bed. Similarly the potassium zincate formed by the slow anodic reaction at the bottommost portion of the anode bed **34** will percolate slowly back into the main flow of electrolyte.

Current may be drawn from fuel cell **2** by closing the circuit between cathode **14** and anode current collector **18** and applying a load. Current drawn through a fuel cell stack is facilitated by connecting the end plates and individual fuel cells are connected, for example with contact pin **22**, and applying a load. In some embodiments a current density of 50 mA/cm^2 or greater is drawn by the load and discharge occurs for periods ranging from 1 to 20 hours. In some embodiments fuel cell **2** or fuel cell stack **10** is maintained in a substantially fully charged state even in a suspended state of active reaction by disconnecting the load. A substantially fully charged state of fuel cell **2** or fuel cell stack **10** is preserved by maintenance of a fully filled anode bed **34**.

Formation of a uniform bed of particles **30** on anode current collector **18** is also facilitated by providing a uniform flow of the electrolyte through anode chamber **16**. Uniform flow is achieved by providing a substantially continuous pressure drop in a downstream direction in anode chamber **16** and minimal or substantially no lateral pressure drop. In some embodiments, electrolyte throughout anode chamber **16** moves at substantially the same flow velocity, with substantially no areas of recirculation or "dead zones" of little or no flow.

In some embodiments, the flow rate of the electrolyte in anode chamber **16** ranges from 1 L/min. to 7 L/min., or 3 L/min. to 7 L/min., or 3 L/min. to 5 L/min.

In some embodiments, electrolyte is loaded into anode chamber **16** at a gauge pressure ranging from 0.69 kPa to 103.4 kPa, or 6.9 kPa to 82.7 kPa, or 13.8 kPa to 68.9 kPa. In some embodiments, the gauge pressure of electrolyte in the anode chamber is less than 34.5 kPa. Gauge pressure refers to pressure zero-referenced against atmospheric air pressure (i.e., the difference between absolute pressure and atmospheric pressure).

FIG. **7** shows a metal-air fuel cell system **200** according to one embodiment of the invention. System **200** includes a fuel cell **210**, an electrolyzer **220** and a fresh fuel tank **230**. Fuel cell **210** may for example comprise a fuel cell **2**. Fuel cell **210** may also comprise a plurality of fuel cells **2** to form a fuel cell stack. One or more pumps (not shown) pump electrolyte and metal particles and/or product species through system **200**. In particular, spent fuel (e.g., oxidized metal, such as zincate) is pumped from the outlet of fuel cell **210** to tank **230** where it can be stored. The spent fuel can then be pumped from tank **230** to electrolyzer **220**. In some embodiments, spent fuel may be pumped from fuel cell **210** directly to electrolyzer **220**. Electrolyzer **220** regenerates the metal fuel, which is subsequently pumped to tank **230**. The metal fuel may for example be dendritic zinc powder ranging in size from 5 nm to 1 mm, 5 nm to 0.5 mm, or 5 nm to 0.3 mm. This metal fuel is stored in tank **230** until required for use by fuel cell **210**. In some embodiments regenerated metal fuel may be pumped directly back into fuel cell **210**.

Where a component (e.g. cathode, anode current collector, etc.) is referred to above, unless otherwise indicated, reference to that component should be interpreted as including as equivalents of that component any component which performs the function of the described component (i.e., that is functionally equivalent), including components which are not structurally equivalent to the disclosed structure which performs the function in the illustrated exemplary embodiments of the invention.

This application is intended to cover any variations, uses, or adaptations of the invention using its general principles. Further, this application is intended to cover such departures from the present disclosure as come within known or customary practice in the art to which this invention pertains and which fall within the limits of the appended claims. Accordingly, the scope of the claims should not be limited by the preferred embodiments set forth in the description, but should be given the broadest interpretation consistent with the description as a whole.

What is claimed is:

1. A method of charging a metal-air fuel cell, the method comprising the steps of:

(a) orienting an anode chamber horizontally wherein a corresponding anode current collector is positioned below the anode chamber, the anode current collector comprising a plurality of particle collectors projecting into the anode chamber;

(b) providing metal particles suspending in an electrolyte to flow through the anode chamber in a downstream direction orientated horizontally;

(c) allowing a bed of the metal particles to form on the anode current collector, wherein the plurality of particle collectors perturb the flow of the electrolyte through the anode chamber and encourage settling of the metal particles one of on and between the particle collectors; and

(d) maintaining uniform formation of the bed.

2. The method according to claim **1**, wherein step (c) comprises at least one of:

(i) maintaining the flow of the metal particles suspended in the electrolyte at a predetermined flow rate; and

(ii) periodically stopping the flow of the metal particles suspended in the electrolyte.

3. The method according to claim **2**, wherein step (d) comprises providing a uniform flow of the electrolyte through the anode chamber.

4. The method according to claim **3**, wherein providing the uniform flow comprises providing a continuous pressure drop in a downstream direction in the anode chamber and a minimal pressure drop in a direction normal to the downstream direction.

5. The method according to claim **4**, wherein providing the continuous pressure drop in the downstream direction and the minimal pressure drop in the direction normal to the downstream direction comprises providing one of a parallel flow and a serpentine flow path for the anode chamber.

6. The method according to claim **3**, wherein a flow velocity of the electrolyte in the anode chamber ranges from 1 cm^3/s to 5000 cm^3/s.

7. The method according to claim **6**, wherein a flow rate of the electrolyte in the anode chamber ranges from one of 1 L/min. to 7 L/min, 3 L/min. to 7 L/min, and 3 L/min. to 5 L/min.

8. The method according to claim **7**, wherein a gauge pressure of the electrolyte in the anode chamber ranges from one of 0.69 kPa to 103.4 kPa and 13.8 kPa to 68.9 kPa.

9. The method according to claim **8**, wherein a pressure drop traversing the anode chamber is less than 103.4 kPa.

10. The method according to claim **9**, wherein the metal particles are zinc particles and the electrolyte is aqueous potassium hydroxide.

11. The method according to claim **10**, further comprising a step of drawing a current density of at least 50 mA/cm^2 from the fuel cell.

12. The method according to claim **11**, further comprising a step of applying a load to the fuel cell.

13. The method according to claim **12**, further comprising a step of discharging for a period of 1 to 20 hours.

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